UDC 666.1.031.13:532.5

NUMERICAL SIMULATION OF EXTERNAL HEAT EXCHANGE IN A GAS-ELECTRIC GLASS-MAKING FURNACE WITH A HORSESHOE FLAME ARRANGEMENT

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Translated from *Steklo i Keramika*, No. 5, pp. 21 – 25, May, 2008.

A numerical simulation of the external heat exchange in a gas-electric glass-making furnace is examined. It is shown that the intensity of additional electric heating (AEH) of the glass mass affects the normal operation of the furnace. Examples of the calculation of the parameters of heat exchange as a function of the furnace productivity and AEH are presented.

The modern period of the development of the glassware industry is characterized by continually increasing specific productivity of furnaces. This trend is due to not only the use of high-productivity glass-forming equipment but also the drive to decrease furnace construction and operating expenses. Experience shows that for flame furnaces with a dinas-brick crown the maximum specific output of glass mass is $P_{sp} = 2.5 – 2.6$ tons/(m^2 · day). For a furnace with effective thermal insulation on the refractory masonry, an efficient structure of the melting tank, and a heat recovery unit, the specific consumption of heat does not exceed 4800 kJ/kg (about 1150 kcal/kg) [1].

It is known that high specific output of glass mass becomes possible if the required amount of heat can be transferred into the melting tank (the zone of the technological process) and the time required for completing the entire set of physical – chemical reactions of glassmaking can be provided. Since radiative heat transfer plays the dominant role in high-temperature furnaces, it becomes understandable that the specific output depends on the temperature of the masonry of the top structure [2]. Calculations show that in a glass-making furnace with horseshoe-shaped flame orientation and specific glass-mass output greater than 2.6 tons/(m^2 · day) the maximum local temperature of the crown can exceed 1600°C. It is obvious that this temperature is not compatible with long-term operation of the known refractory materials, including electro-smelted AZS parts with a low content of the glass phase.

Thus, on the basis of the specific output 2.6 tons/(m^2 · day) it becomes desirable to use additional electric heating (AEH) of the glass mass in the melting tank. Three problems can be solved in doing so:

the heat stress on the masonry of the working space can be decreased;

the specific consumption of heat for glass making can be decreased;

the required productivity of the furnace can be attained without increasing the area of the melting tank.

In spite of the obvious advantages of gas-electric method for heating furnaces, in practice the use of AEH is a quite difficult engineering problem, whose correct solution is inconceivable without preliminary mathematical simulation of the thermophysical processes of glassmaking.

We are considering this subject because of the need to solve a concrete problem. The problem is to design a glass-making furnace with a horseshoe-shaped orientation of the flame with productivity 320 tons/day for making colored glasses. Two 12-section machines with three-drop feeding are to be used to produce the glass parts. The high requirements for thermal uniformity of the glass during production of light glassware by the NNPB gives a basis for a maximum specific output of 2.7 – 2.8 tons/(m^2 · day), taking the area of the melting tank of the furnace to be 116 – 118 m^2.

Of the known methods for using AEH to intensify the thermal operation of furnaces, the most widely used one is feeding electric power into the zone of silicate and glass formation through the side walls and (or) the bottom of the melting tank. It is obvious that additional electric heating of the glass mass will result in definite changes in the heat-transfer processes in the tank as well as in the hydrodynamics of the melt. The possibility of decreasing the heat stress in the working space of the furnace by introducing a portion

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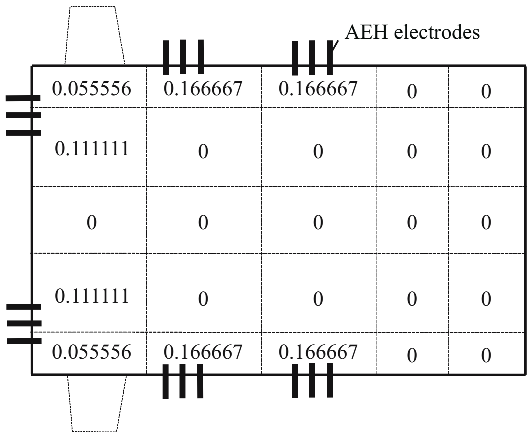

Fig. 1. Diagram of the distribution of heat release from AEH along the surface zones of the glass as (as a fraction of the total AEH power).

of the heat energy required for making glass directly into the tank by means of AEH is examined in the present work.

We recall that the coupled mathematical model which we developed for heat transfer in a glass-making furnace is based on the assumption of relative autonomy of the external and internal heat exchanges which on the heat-transfer level are related only through the heat flux density on the surface of the glass mass [3, 4]. Consequently, to a first approximation, the variation introduced by AEH in the temperature fields in the working space can be analyzed without taking account of the motion and heating of the melt in the furnace tank. Then, on the basis of the numerical model of external heat exchange, the AEH energy appears in the free term in the zonal equations governing heat exchange between the surface zones of the glass mass, taking account of the internal and external sources and sinks of heat [5].

The external heat exchange was analyzed for a variant of AEH by means of electrodes placed in the side walls of the melting tank before the separation threshold. The distribution of the thermal power of AEH over 25 surface zones of the glass mass is shown in Fig. 1. Furnace productivity $P = 300$ tons/day $[P_{sp} = 2.591$ tons/(m$^2 \cdot$ day)] and natural gas consumption 1732.9 m^3/h were taken as the base variant. The lower working heating capacity of the fuel Q^1_w was taken as 35.042 MJ/m^3. The total AEH power was varied in the range 200 – 1000 kW.

The effect of AEH on the possible decrease of fuel consumption and the associated change of the temperature fields on the surface of the glass mass and crown was investigated in the first series of calculations. A special method for analyzing the results of the zonal calculations [6] made it possible to determine the average temperature of the surfaces $\bar{t}$ and their maximum values t_{max} with coordinates along the longitudinal x_{max} and transverse y_{max} axes of the furnace.

For prescribed electric heating power Q_e, the fuel consumption B was varied until the following conditions were satisfied simultaneously:

the maximum temperature of the surface of the glass mass about 1500°C; it is assumed that this temperature level is, to a certain extent, a limiting value for long-time operation of the refractory masonry of the melting tank and simultaneously sufficient for obtaining high-quality glass mass;

the surface-averaged temperature of the glass mass differs very little from the base value: the standard deviation δ_σ of two temperature fields (for the base variant and in the presence of AEH) does not exceed 30°C.

The standard deviation was calculated using the relation

$$\delta_\sigma = \sqrt{\frac{1}{136 \times 85} \sum_{i=0}^{136} \sum_{j=0}^{85} [t(x_i, y_j) - t_{Q_e}(x_i, y_j)]^2},$$

where $x_j = 0.1i$, $y_j = 0.1j$ ($i = 0 – 136$, $j = 0 – 85$) are the longitudinal and transverse coordinates of the computational node, m; $t(x_i, y_j)$ and $t_{Q_e}(x_i, x_j)$ are, respectively, the surface temperature, °C, of the glass mass at a node in the base variant of furnace operation and in the presence of AEH.

The similar standard deviation was also determined for the temperature fields of the furnace crown.

The computational results show that AEH has an appreciable effect on the character of heat-exchange processes in the working space of the furnace. This influence is manifested in the temperature distribution on the surface of the crown and of the glass mass (Fig. 2) as well as in the quantitative parameters of heat exchange (Table 1). It is evident that on the one hand completely predictable characteristics

TABLE 1.

Q_e, kW	B, m^3/h	Glass mass surface					Crown surface				
		t^{gl}_{max}, °C	x_{max}, m	y_{max}, m	$\bar{t}_{gl}$, °C	δ_σ, °C	t^{cr}_{max}, °C	x_{max}, m	y_{max}, m	$\bar{t}_{cr}$, °C	δ_σ, °C
0	1732.9	1503.1	10.29	2.15	1374.7	–	1603.4	8.21	1.35	1478.2	–
200	1707.8	1499.5	10.28	2.22	1376.2	6.11	1601.6	8.15	1.34	1477.8	1.99
400	1682.1	1495.9	10.28	2.37	1377.8	12.15	1599.8	8.09	1.33	1477.3	4.00
600	1657.0	1500.8	8.89	0	1378.9	18.12	1598.0	8.03	1.31	1476.9	6.02
800	1632.9	1515.7	8.28	0	1378.9	23.85	1594.9	7.96	1.30	1475.0	8.54
1000	1605.6	1528.9	7.89	0	1380.0	29.70	1593.1	7.90	1.28	1474.5	10.58

are observed while on the other hand some characteristics require special investigation and interpretation.

The initial conditions for the calculation suggest that for constant furnace productivity an increase of AEH power should naturally result in lower fuel consumption and lower temperature on the inner surface of the crown. In the experimental range of variation of the electric-heating power (0 – 1000 kW) increasing the fraction Q_e from 026% of the total thermal power of the furnace ($BQ_w^1 + Q_e$) decreases the fuel consumption by 7.33%. The relation between the fuel consumption and the AEH power is quite accurately (rms deviation $R^2 = 0.9998$) described by the linear function

$$B = 1733.3 - 0.1264Q_e, \text{ m}^3/\text{h}. \quad (1)$$

The character of this function attests to the linear variation of heat release in the working space of the chamber. Consequently, for constant furnace productivity, an increase of the AEH fraction in the total thermal power of the working space results in a linear variation of the maximum temperature of the crown surface ($R^2 = 0.9909$):

$$t_{\max}^{\text{cr}} = 1603.7 - 0.0105Q_e, \text{ °C}.$$

At the same time the maximum temperature of the glass mass surface decreases with increasing Q_e only until the coordinates of the maximum remain virtually constant. When the extremum point shifts toward the burner entrance, increasing the AEH power increases $t_{\max}$. As a result we obtain a parabolic dependence ($R^2 = 0.9812$):

$$t_{\max}^{\text{gl}} = 1503.7 - 0.0445Q_e + 7 \times 10^{-5}Q_e^2, \text{ °C}.$$

It is interesting that when AEH is introduced through the side walls of the melting tank increasing the fraction Q_e does not substantially change the glass mass temperature averaged over the surface of the tank. The magnitude of the differences in the values of $\bar{t}_{\text{gl}}$ lies within the error of the zonal method and equals about 0.5°C per 100 kW of AEH power ($R^2 = 0.9378$):

$$\bar{t}_{\text{gl}} = 1375.2 + 0.0051Q_e, \text{ °C}. \quad (2)$$

At the same time the average temperature of the crown surface decreases as ($R^2 = 0.9603$)

$$\bar{t}_{\text{cr}} = 1478.2 - 0.0012Q_e + 3 \times 10^{-6}Q_e^2, \text{ °C}.$$

At the applied level it is helpful to examine the influence of the AEH power on heat exchange in the working space of the furnace with a limitation on the maximum temperature of the crown. For this, we introduce an assumption in the initial conditions for the calculation: we take as the main condition for the convergence of the fuel consumption with the introduced AEH power that the requirement for a limit on the maximum local temperature of the crown is satisfied, for example, $t_{\max}^{\text{cr}} = 1580$°C.

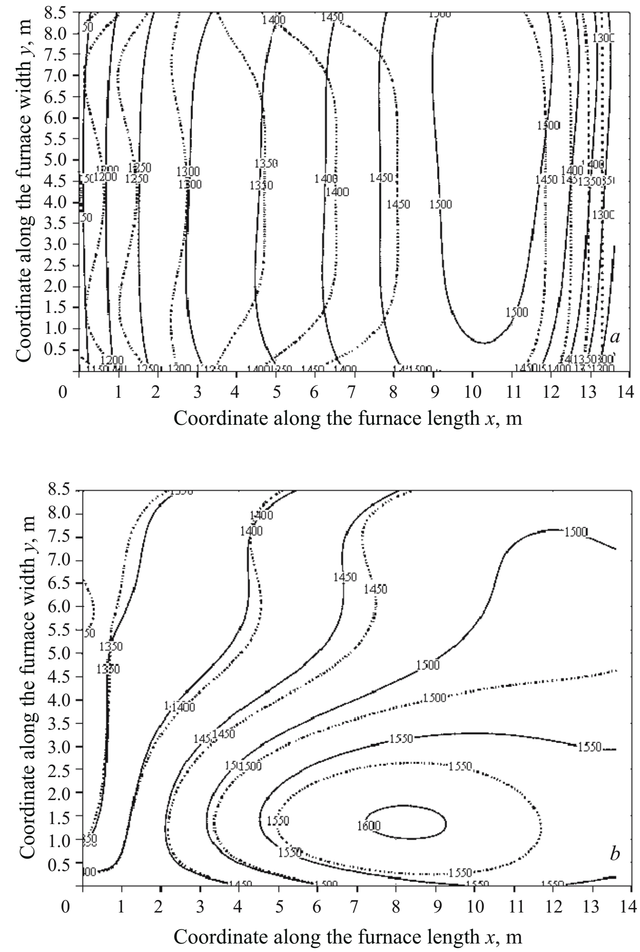

Fig. 2. Temperature fields on the surfaces of the glass mass (*a*) and crown (*b*) with productivity 300 tons/day. $Q_e = 0$ (*solid lines*); $Q_e = 800$ kW (*dotted lines*); the numbers on the curves show the temperature, °C.

The results of the calculations (Table 2) show that setting $t_{\max}^{\text{cr}} = \text{const}$ preserves the linear character of the function $\bar{t}_{\text{gl}} = f(Q_e)$. Compared with Eq. (2) only its quantitative expression changes ($R^2 = 0.9996$):

$$\bar{t}_{\text{cr}} = 1345.4 + 0.0185Q_e, \text{ °C}.$$

Setting $t_{\max}^{\text{cr}} = 1580$°C also changes the quantitative characteristic of Eq. (1). The relation between the fuel consumption and the AEH power can be approximated by the expression ($R^2 = 1$)

$$B = 1695.8 - 0.1095Q_e, \text{ m}^3/\text{h}.$$

In addition, the standard deviations with respect to the temperature of the crown and glass mass surfaces increase somewhat. For example, they equal 35.93 and 30.05°C, respectively, for the glass mass temperature and 200 and 800 kW for Q_e. For the crown temperature the deviation is 17 and 20°C ($Q_e = 1000$ kW). Since the values of δ_σ, in con-

TABLE 2.

Q_e, kW	B, m^3/h	Glass mass surface				Crown surface*		
		t^{gl}_{max}, °C	x_{max}, m	y_{max}, m	$\bar{t}_{gl}$, °C	x_{max}, m	y_{max}, m	$\bar{t}_{cr}$, °C
0	1695.7	1474.4	10.289	2.42	1345.2	8.14	1.36	1456.0
200	1674.0	1473.1	10.286	2.64	1349.1	8.07	1.34	1455.7
400	1652.1	1472.2	10.280	5.60	1352.9	8.01	1.33	1456.4
600	1630.2	1480.5	8.880	0	1356.6	7.95	1.31	1457.3
800	1608.2	1496.0	8.323	0	1360.2	7.90	1.30	1459.3
1000	1586.2	1515.1	7.873	0	1363.7	7.85	1.28	1460.8

* Given: t^{cr}_{max} = const = 1580°C.

trast to the conditions for t^{gl}_{max} and t^{cr}_{max}, have no fundamental significance at the applied level; the results of this series of calculations are of practical interest.

It follows from the data in Table 2 that for $Q_e < 800$ kW the limitation introduced $t^{cr}_{max} = 1580$°C makes it impossible to satisfy the condition for $t^{gl}_{max} \approx 1500$°C. This is because a decrease of fuel consumption to a level for which t^{cr}_{max} = 1580°C decreases the heat emission from the flame in the masonry of the working space onto the surface of the glass mass. The amount of heat transferred by this surface as a result of AEH power is inadequate to maintain its temperature (see Table 1, $Q_e = 0$). Increasing the AEH power ($Q_e \approx$ 800 kW) makes it possible not only to satisfy the condition for $t^{cr}_{max} = 1580$°C and $t^{gl}_{max} = 1500$°C but also to decrease the total heat load of the furnace (about 2%). Compared with the base variant, the average temperature of the glass mass surface decreases very little. A positive result of AEH with power $Q_e = 800 - 1000$ kW is that the longitudinal coordinate (x_{max}) of the maximum temperatures of the crown and glass mass surfaces is the same, which greatly simplifies the construction of the melting tank.

The data in Table 2 also make it possible to conclude that the furnace productivity 300 tons/day assumed in the calculations for the prescribed initial conditions can be achieved with $Q_e = 800$ kW. Increasing the AEH power to 1000 kW creates the prerequisites for increasing the furnace productivity, which the data in Table 3 confirm.

The fact that the glass-making furnace productivity can realistically reach the value indicated in Table 3 with the prescribed AEH power and the computed value of the fuel consumption can be checked by the values of the specific heat consumption for glassmaking. Analysis of the data in Table 4 shows that they reflect quite accurately the qualitative and quantitative dependence of the specific heat consumption q_{sp} on the specific productivity of modern glassmaking furnaces. This confirms the possibility of using the methodology examined above for analyzing the normal operation of gas-electric glassmaking furnaces with horseshoe flame arrangement.

Figure 3 displays the temperature field on the surfaces of the glass mass and crown for $P = 325$ tons/day and $Q_e = 1000$ kW, $t^{cr}_{max} = 1580$°C. Analysis of the analogous temperature fields for $P = 300 - 380$ tons/day and $Q_e = 1000 - 1500$ kW made it possible to obtain a series of two-dimensional equations which are required for a preliminary calculation of the gas-electric furnaces: $B = f(P, Q_e)$, $t^{gl}_{max} = f(P, Q_e)$, $\bar{t}_{gl} = f(P, Q_e)$, $\bar{t}_{cr} = f(P, Q_e)$, and so forth. These functions can be used to calculate certain characteristics of the furnace which are necessary for forming and checking its heat balance. As an example, we present a calculation of the parameters of a glassmaking furnace with productivity 350 tons/day [$P_{sp} = 3$ tons/(m^2 · day)] and $t^{cr}_{max} = 1580$°C (Table 5).

In conclusion, we note that the proposed method of numerical simulation of external heat exchange in a gas-electric glassmaking furnace can be used for an approximate analysis of different arrangements of the AEH electrodes in the melting tank of the furnace. The temperature fields of the glass mass can be treated as initial conditions for a more detailed

TABLE 3.

P, tons/day	Q_e, kW	B, m^3/h	Glass mass surface				Crown surface			
			t^{gl}_{max}, °C	x_{max}, m	y_{max}, m	$\bar{t}_{gl}$, °C	t^{cr}_{max}, °C	x_{max}, m	y_{max}, m	$\bar{t}_{cr}$, °C
300	1000	1586.2	1515.1	7.87	0	1363.7	1580	7.85	1.28	1460.8
320	1000	1681.4	1507.3	8.01	0	1349.9	1580	7.91	1.28	1456.0
325	1000	1704.6	1505.5	8.04	0	1346.5	1580	7.92	1.28	1454.8

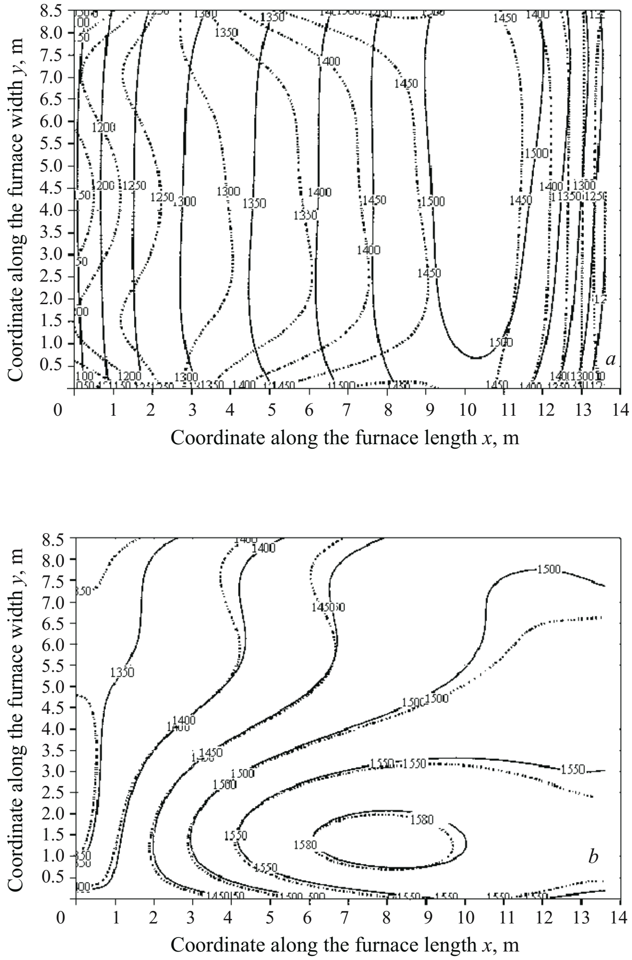

Fig. 3. Temperature fields on the surfaces of the glass mass (*a*) and crown (*b*) with productivity 325 tons/day. $Q_e = 0$ (*solid lines*); $Q_e = 1000$ kW (*dotted lines*); numbers on curves) temperature, °C.

investigation of the hydrodynamics of glass melt in the melting tank.

TABLE 4.

P, tons/day	P_{sp}, tons/(m^2 · day)	Q_e, kW	B, m^3/h	$(BQ_w^l + Q_e)$, MW	q_{sp}, kJ/kg (kcal/kg)
300	2.591	–	1695.7	16.506	4753.7 (1135.6)
300	2.591	1000	1586.2	16.440	4734.7 (1131.1)
320	2.764	1000	1681.4	17.366	4688.4 (1120.0)
325	2.807	1000	1704.6	17.592	4676.8 (1117.3)

TABLE 5.

Indicator	Computational parameters of the furnace for AEH power, kW					
	1000	1100	1200	1300	1400	1500
B, m^3/h	1810.9	1798.9	1786.9	1774.9	1762.9	1750.9
$\bar{t}_{gl}$, °C	1328.5	1330.3	1332.2	1334.1	1335.9	1337.8
t_{max}^{gl}, °C	1498.5	1508.6	1520.3	1533.4	1548.1	1564.2
$\bar{t}_{cr}$, °C	1449.0	1450.6	1452.4	1454.3	1456.4	1458.5
q_{sp}, kJ/kg	4599.3	4595.1	4591.0	4586.8	4582.7	4578.5

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